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Low Q Spin-up from Rest

Final Report

Keith D. Aldridge

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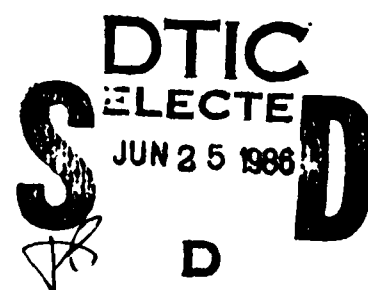| REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
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Decay rates, eigenfrequencies, inertial waves, liquid filled shells, non-Newtonian fluids, resonance, resonant collapse, spin-up.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Eigenfrequencies and decay rates of inertial waves have been measured for both Newtonian and non-Newtonian fluids contained in a cylindrical cavity while the fluid spins up from rest. The waves were excited by precessing the lid of the container until resonance was reached and detected by measuring disturbance pressure differences while the waves decayed freely. Measurements extend from 0.5 spin-up times to steady state and over a range of Reynolds numbers 100–45,000 for the Newtonian fluids with precession amplitudes in the range 0.006–0.0328 radians.

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Measured eigenfrequencies agree to within a few percent with those calculated by Sedney at Ballistic Research Laboratory. Decay rates compare less favorably because they are more difficult to measure experimentally and to calculate theoretically.

New methods of analysis were developed to recover the eigenfrequencies and decay rates. Previously used iterative techniques were modified to allow for the removal of the effects of recording filters and also automate the procedures used made possible with improved estimates of errors.

New results for non-Newtonian fluids which show shear thickening are presented. These fluids have anomalous behaviour in the dependence of eigenfrequency and decay rate on time since the container's rotation began compared to that of a Newtonian fluid.

Resonant collapse observed at larger amplitudes of precession has been interpreted as loss in resonant amplitude associated with the mean azimuthal flow. This interpretation is consistent with experimental observation that the full reappearance of an inertial wave can sometimes take place after it collapses.

Single ended measurements of pressure at the fluid boundary were found to be consistent with the hypothesis that the inertial wave studied was a standing rather than a travelling wave. For a right circular cylinder, by contrast, it has been proven that nonaxially symmetric inertial waves are travelling disturbances.

The possibility of inhibiting inertial waves through critical damping has been demonstrated in a pilot study. Modification of boundaries may make it possible to restrict the inertial wave response of a fluid cylinder so that previously observed flight instabilities of liquid filled shells caused by inertial wave torques could be eliminated.

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1   Problem Studied

This project has been concerned with the measurement and interpretation of inertial waves excited in a fluid contained in a rotating cylindrical cavity. Non–axisymmetric inertial waves are well known to play a central role in producing flight instabilities in spin–stabilized fluid filled projectiles. Since observed flight instabilities can occur before the fluid has spun up to steady rotation, it is necessary to know the properties of these waves during spin–up from rest. Accordingly, measurements of eigenfrequencies and decay rates for inertial waves in a cylindrical cavity were made throughout spin–up of the contained fluid. Where possible, comparison has been made with predictions from theoretical work by Dr. R. Sedney at Ballistic Research Laboratory.

The term low Q has been used to describe the regime studied in our experiments. For a simple oscillator, Q is the reciprocal of the fractional loss in energy per cycle during free decay. High damping or low Q was anticipated for the inertial waves at early time during spin–up from rest, even with relatively inviscid fluids, and at later (steady state) times for the more viscous ones.

Inertial waves were excited in our experiments by precessing the lid of the cylindrical cavity at a frequency near the expected resonance for a given rotation speed. Freely decaying waves were detected by measurement of disturbance pressure differences between various points on the boundary of the fluid. By varying the shutoff time of the drive exciting the waves, a study of the resonance was made for various times during spin–up from rest.

The complex eigenfrequencies (eigenfrequencies and decay rates) for the inertial waves were recovered from digitally stored records of the disturbance pressure differences by modelling the signal as an appropriate number of decaying sinusoids. Optimal values of the unknown parameters were found ultimately by minimizing the sum of the squares of the differences between the actual and model data. These experimentally determined complex eigenvalues were compared to predicted ones calculated at Ballistic Research Laboratory.

For a fluid which is in so–called solid body rotation, the ratio of pertur-

bation frequency to rotation speed for inertial wave resonance is well known for a perfect (zero viscosity) fluid from theoretical work dating back to Lord Kelvin. For a fluid of finite viscosity, correction to these resonances as well as the decay rates come from more recent calculations by Greenspan (1969) and others. Eigenfrequencies and decay rates for a fluid of finite viscosity during spin–up of the fluid from rest have only recently been available from work by Sedney and Gerber (1983) at Ballistic Research Laboratory.

Collapse of the inertial wave resonance, which was observed in earlier studies both in our laboratory and others, was considered in this project. This phenomenon was characterized by an irregular reduction in the envelope of disturbance pressure amplitude while the lid was still precessing both during spin–up and later when the fluid was essentially rotating as a solid body. Resonant collapse may play an important role in the stabilization of liquid filled projectiles since the resonance itself almost disappears when collapse takes place. A theoretical model for its onset has been formulated.

The fluids used in these experiments were primarily silicone oils with nominal kinematic viscosities varying from 1cs to 350 cs. Exception to this was a set of experiments using a non–Newtonian fluid consisting of a 0.5% solution of Sodium Carboxymethyl cellulose in distilled water.

2 Summary of Most Important Results

The free ringdown of inertial waves in a cylindrical cavity has been studied both experimentally and theoretically in this project. Eigenfrequencies and decay rates for Newtonian fluids (silicone oils) with Reynolds numbers in the range 100–45,000 as well as a non–Newtonian fluid have been measured both during spin–up from rest and at steady state. The fluids were contained in a cylindrical cavity of radius and height respectively 9.53 and 11.437 centimeters. Measurements over a range of precession amplitudes (0.006 – 0.328 radians) for several of these cases showed the effects of finite amplitude forcing. Resonant collapse has been observed at larger amplitudes and a model for the onset of this collapse has been developed. Approximately 355 records of free decay of inertial waves have been obtained and processed to determine eigenfrequecies and decay rates.

Single ended disturbance pressure measurements have revealed that during free ringdown, the inertial waves are standing rather than travelling waves for the case of a tilt of the upper boundary of 0.0328 radians. This result is particularly significant because it has long been known that for a fluid contained in a right circular cylinder, all non–axially symmetric inertial waves exist as travelling disturbances.

A set of pilot experiments not included in the work proposed under this contract has led to a design for the likely critical damping of inertial waves in a fluid contained in a closed cylindrical cavity.

Sample results from each of these areas are described in the following sections.

2.1 Recovery of Complex Eigenfrequencies

The procedure for the recovery of complex eigenfrequencies from disturbance pressure observations has evolved significantly during this work. In general, more recent processing methods require fewer assumptions about the data than earlier ones. The complex eigenfrequencies reported below were obtained using one of two methods of analysis, which are referred to here as stacked records, linearized least squares (2.1.1) and pre–filter, sequential fitting (2.1.2), both of which are described in the following sections.

2.1.1 Stacked records, Linearized Least Squares

Disturbance pressure data from each of four pairs of measurement points on the base of the cylinder are cross–correlated and then averaged to improve the signal–to–noise ratio. The averaged data is then modelled as one or more exponentially damped sinusoids whose frequencies may be allowed to depend on time because the resonant conditions themselves depend on the fraction of fluid which has spun up. The L–2 norm between the model and the data is minimized with respect to complex eigenfrequencies after linearization of the model by Taylor expansion. Details of this method are reported by Aldridge and Stergiopoulos (1985).

Complex Eigenfrequencies vs Reynolds Number   Shown in Figure 1 are the recovered eigenfrequencies in steady state for the (1,1,1) mode (lower) and the (1,2,1) mode (upper) for a of series of Reynolds numbers in the range 100 to 45000. Here Reynolds number is defined as

$$Re = \frac{\Omega a^2}{\nu}$$

and

$$C_r = 1 - \frac{\omega}{\Omega}$$

where ω is the recovered eigenfrequency, Ω is the container's rotation speed, a is the radius of the cylinder and ν the kinematic viscosity. Steady state refers to times greater than approximately 4 spin–up times since the container began rotating from rest. Error bars shown in the figure are calculated assuming that the residual noise which remains after the recovery is uncorrelated. The small F at lower values of Reynolds number is a value of C_r obtained using the driving frequency of the lid rather than the recovered eigenfrequency.
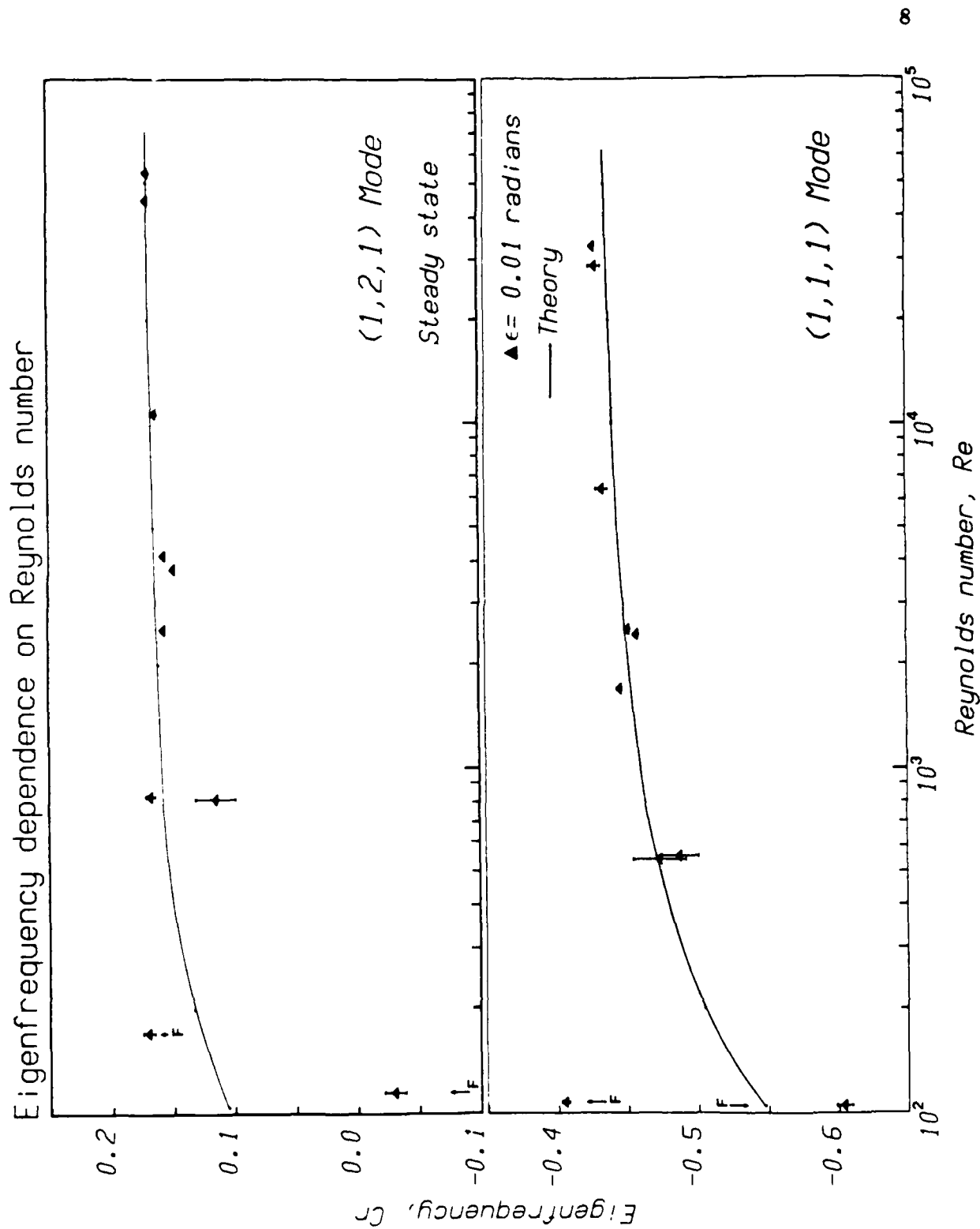
Figure 1. Measured (triangles) and calculated (lines) eigenfrequencies for the (1,1,1) and (1,2,1) modes as a function of Reynolds number for a cylinder in solid body rotation. Theoretical prediction is from Sedney (1983). The symbol F represents the value of C_r found using the forcing frequency. Precession amplitude of lid is 0.01 radians.

The lines shown in both panels of the figure are eigenfrequencies calcu-
lated by Sedney (1983) at Ballistic Research Laboratory.

A small decrease in C_r with decreasing Reynolds number is evident
in the experimental results and this is also shown by the prediction. For
Reynolds numbers less than about 1000 there is less certainty in the experi-
mental results. The assumption of uncorrelated noise for Reynolds numbers
less than 200 is no longer appropriate so that the error bars shown there
represent only a portion of the total error. Recent analysis of the individual
records in this region show that critical damping may already have been
reached.

The dependence of decay rate on Reynolds number from the same set
of experiments as used for Figure 1 is shown in Figure 2. The decay rate C_i
is the measured (dimensional) rate of decay divided by the rotation speed.
Experimentally determined decay rates are shown by the solid triangles and
squares. The open triangles and squares are predicted decay rates obtained
from Sedney (1983) and the lines are from calculations by Murphy (1983).

The measured decay rates are less reliable at smaller Reynolds numbers
because the signal–to–noise ratios become small there and there is signifi-
cant interaction among the modes. There appears to be a large discrepancy
between prediction and observation at low Reynolds numbers for the (1,2,1)
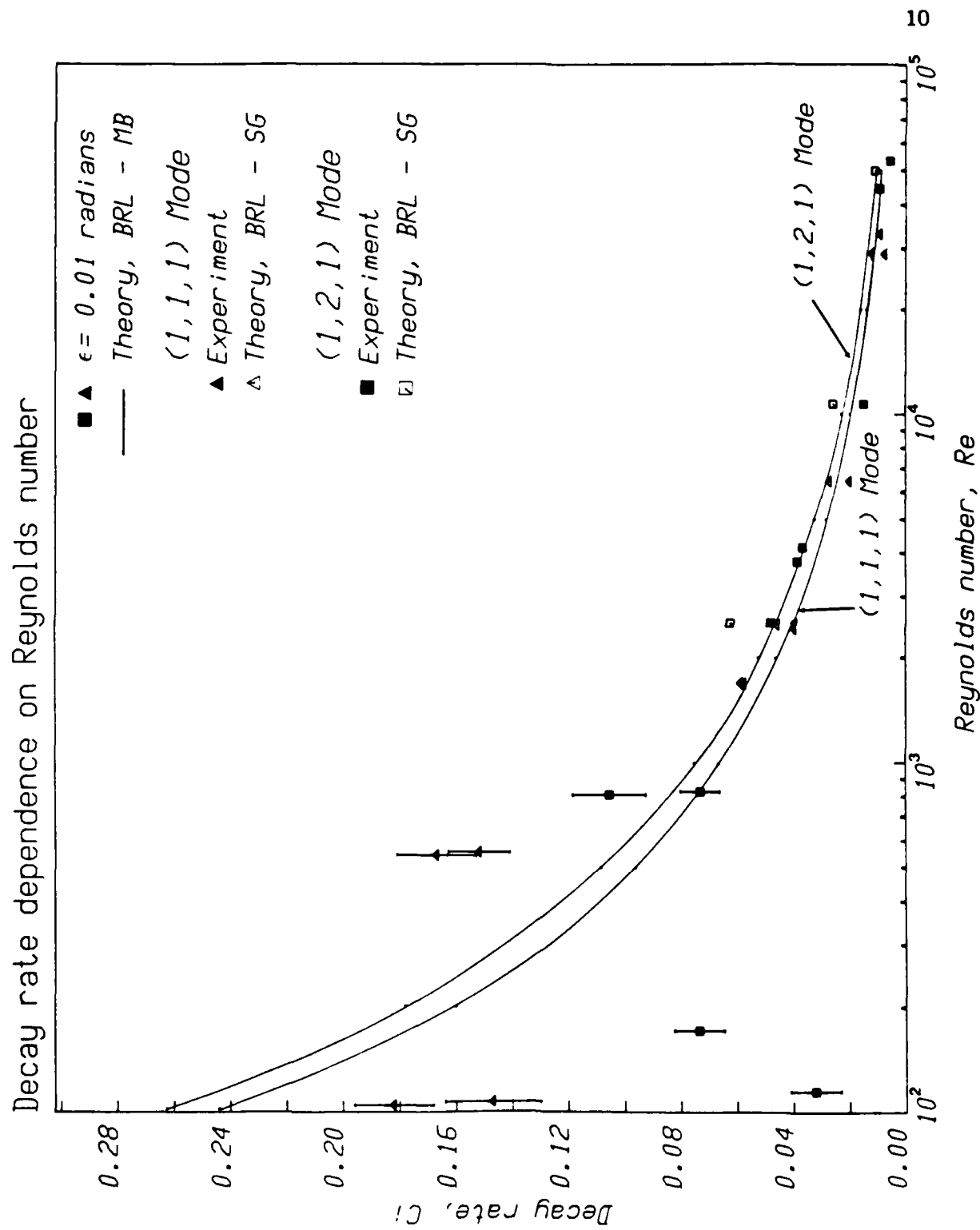mode.

Decay rate dependence on Reynolds number

Figure 2. Measured and calculated decay rates for the (1,1,1) and (1,2,1) modes as a function of Reynolds number for a cylinder in solid body rotation. Sources for the theoretical work are Sedney and Gerber (SG) and Murphy and Bradley (MB). Precession amplitude of lid is 0.01 radians.

Complex Eigenfrequencies, Time dependence   The stacked record, linearized, least squares method was also used to obtain the dependence of complex eigenfrequency on time since the container began rotating. Figure 3 shows eigenfrequencies for both the (1,1,1) mode and the (1,2,1) mode at three different precession amplitudes. The curves in these figures are from Sedney (1983). While there appears to be agreement between prediction and observation for the smallest amplitude of perturbation, a large scatter exists among the data for larger amplitudes. This scatter is mostly due to interaction among decaying waves at the larger amplitudes.

A typical set of results for decay rates at various times since the container started rotating is shown in Figure 4. Again there is a visible trend for smaller amplitudes, but significant scatter for the largest amplitude of precession.

Several other cases were studied at smaller Reynolds numbers and early times. At smaller Reynolds numbers signal-to-noise ratios decreased and problems arose with the stacked, linearized least squares processing. For this reason other methods were investigated and what follows in the next section is a procedure which was developed to solve these problems. An example of its application to several data sets is given after a description of the technique.
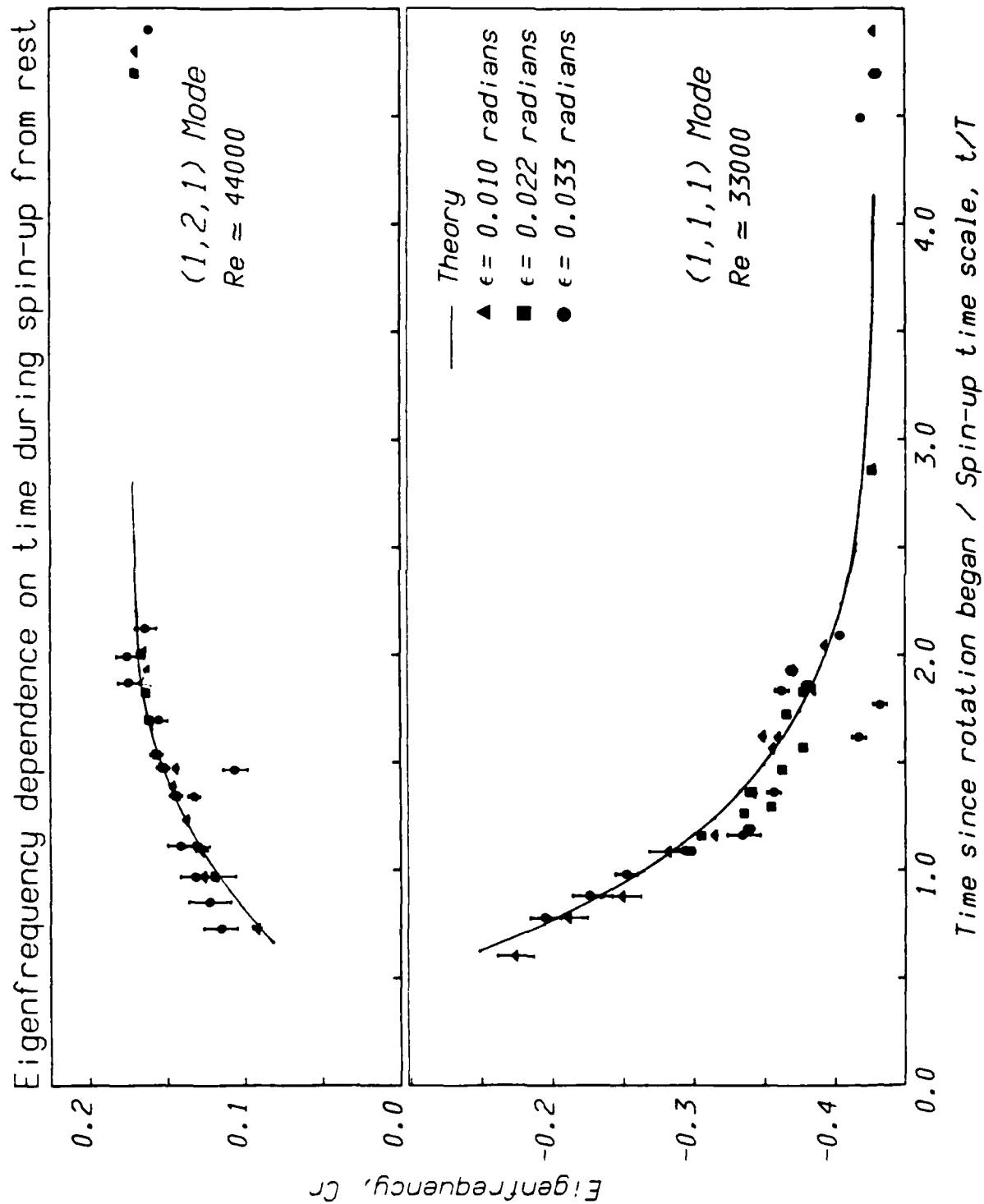
Figure 3. Measured (points) and calculated (lines) eigenfrequencies of the (1,1,1) and (1,2,1) modes for the cylinder during spin-up from rest at three different amplitudes of precession. Calculations were done by Sedney (1983).
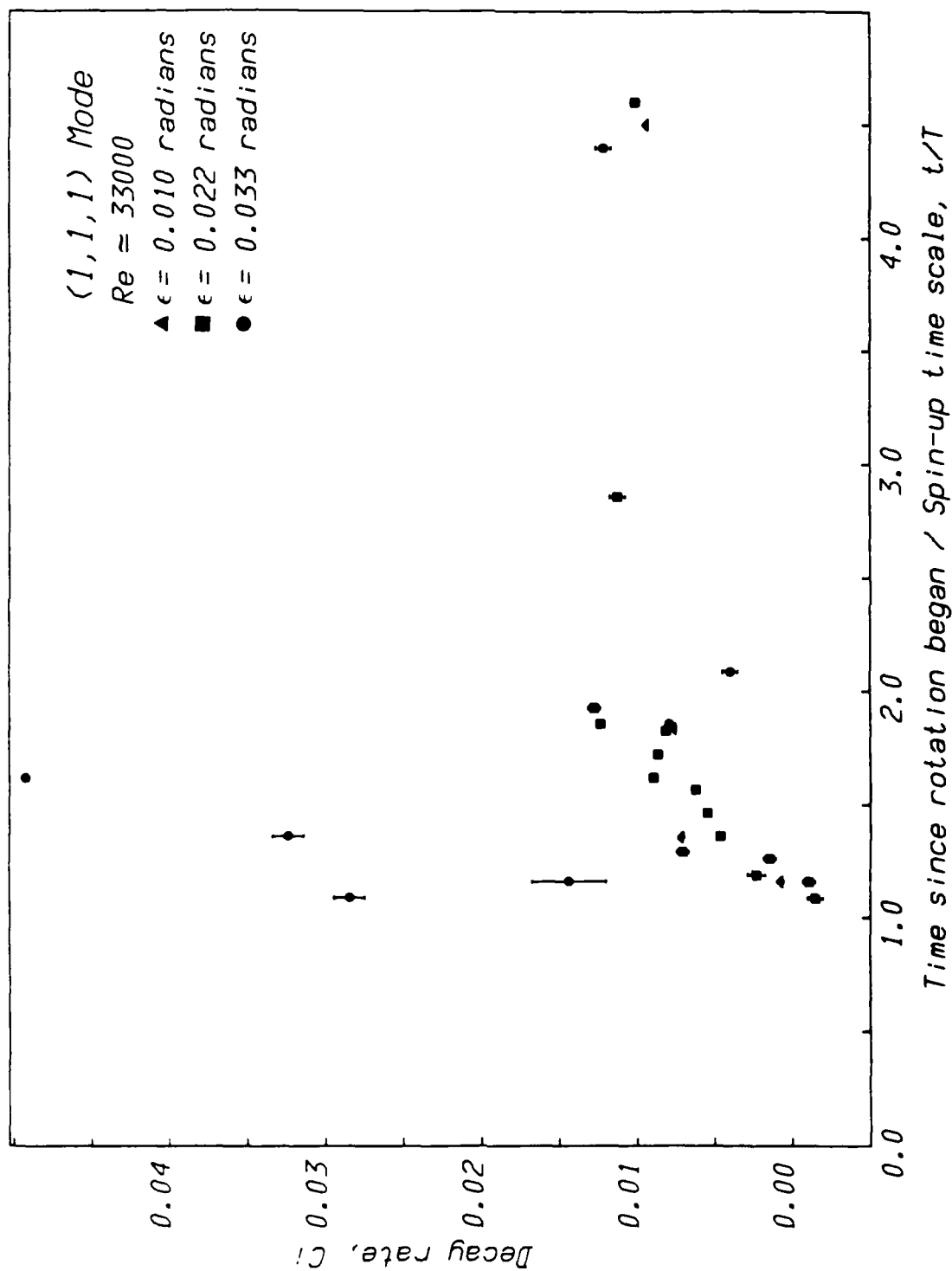
Figure 4. Measured decay rates for the (1,1,1) mode of the cylinder during spin-up from rest at each of three precession amplitudes of the lid.

2.1.2 Pre–filter, Sequential Fitting

Models for free ringdown of the inertial waves in the previous sections were compared to the filtered data in order to optimally recover complex eigenfrequencies. A more precise method than the one described in 2.1.1 is to compare the model with the pressure field at the point of observation in the fluid. Since the pressure field there is filtered before it is recorded, the part of the method developed to do this is entitled pre–filter fitting.

Amplitude resolution in the pressure data was too poor to adequately use a standard deconvolution procedure. Accordingly, a method was devised to compare the model with the input to the filters in another way. Estimates of complex eigenfrequencies were obtained by minimizing the difference between the observed pressure differences and those of the model. It can be shown that convolution of the impulse response of the filter with columns of the coefficient matrix of partial derivatives in our conventional linearized least squares method will accomplish this.

A second problem with the method given in 2.1.1 was a practical one. Computationally, it was sometimes difficult to simultaneously fit several modes at once. Therefore a procedure was developed to sequentially fit one mode after another so that only one set of parameters was updated in any one iteration, the others being fixed by a previous iteration, or by estimation if it was the first cycle.

A further problem with the previous method was associated with the stacking. The averaging procedure included the (slightly different) impulse responses for each of the 4 filters so that it was impossible to remove the effects of the filters individually. Futhermore, some error was introduced by adding the individual records after cross correlation because there was no guarantee that the sample times would match for the shifted records. Hence it was decided to process each of the four records individually and average the results.

All of the processing which yielded the results below was carried out with an initial pseudo–random search of frequencies and decay rates. This step was necessary because initial estimates of the model parameters could no longer be mdae by an inspection of the filtered data. Although this meant significantly more computing time, it had the added benefit that no operator made initial estimates as was done using the stacked record

method of 2.1.1.

Our current method of processing is called pre–filter, sequential fitting and is illustrated in Figure 5 by panels (1) through (8). Panel (1) shows a section of the measured differential pressure of a rotating fluid of Reynolds number 2571 after filtering with a bandpass range of 0.5 – 1.2 Hz. Arrows indicate the shutoff point (1.99 spin–up times) of the precessing lid. Panels (2),(3) and (4) are waveforms which have been fitted to the freely decaying part of (1).

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Cr

− .450

− .972

− .004

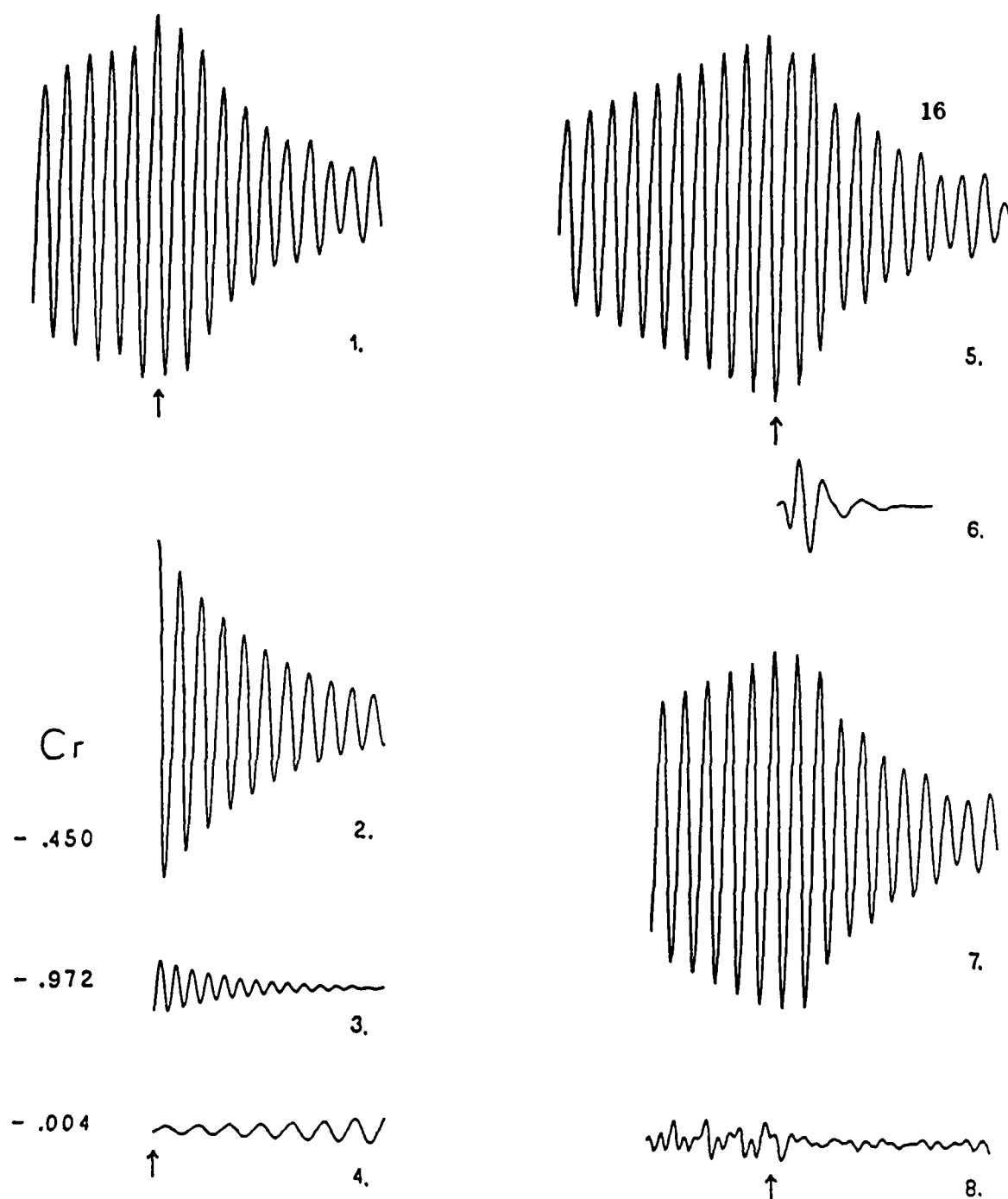Figure 5. Decomposition and reconstruction of a disturbance pressure signal. Small arrow marks the point at which the perturbation was stopped. Panel (1): recorded signal; panels (2), (3) and (4): components of (1) found from pre–filter fitting; (5): reconstructed pressure signal from (2), (3) and (4); (6): impulse response of the filter; (7):convolution of (5) and (6); (8): difference between (1) and (7).

To illustrate that filtering effects have been removed, these are summed together and combined with a waveform recovered from the driven section of the record in (1). The resulting dataset (5), is then filtered by convolution with the measured impulse response of the filter (6), to arrive at (7), the synthetic filtered dataset . The residual (8), i.e. that part of the signal unaccounted for by the fitting procedure, is found by subtracting (7) from the actual recorded (filtered) data (1). The rms value of the residual after shutoff is less than 2.7 percent of the peak amplitude of the actual data. All diagrams except (6) are shown to scale.

The pre–filter, sequential fitting procedure is applied to all the results reported below.

Complex Eigenfrequencies, Early Time Since the effects of recording filters have been removed, the following estimates are the best that can be expected from our data. Finally, and probably most important, 3 modes were recovered where only 1 or 2 had been recovered previously. Hence there should be less bias due to correlated noise which is a problem if modes remain in the record as noise.

The processing has been costly in computer time. It took 41 CPU hours of time on a VAX 8600 to obtain the complex eigenfrequencies presented in this section. Since vastly more real hours are required to obtain this much cpu time, there has been a great delay in obtaining these results.

Figures 6 and 7 show respectively the recovered eigenfrequencies and decay rates using pre–filter, sequential fitting (labelled Reprocessing) on data for the (1,1,1) mode at low Reynolds number and small perturbation amplitude. Also shown in this figure are the results for the stacked record, linearized least squares method. Although there appears to be a greater discrepancy between theory and experiment for the reprocessed eigenfrequency data, a more consistent dependency on time since the rotation began has been found for the decay rates.

Results for the reprocessed data of Figures 6 and 7 are given in Table 1.

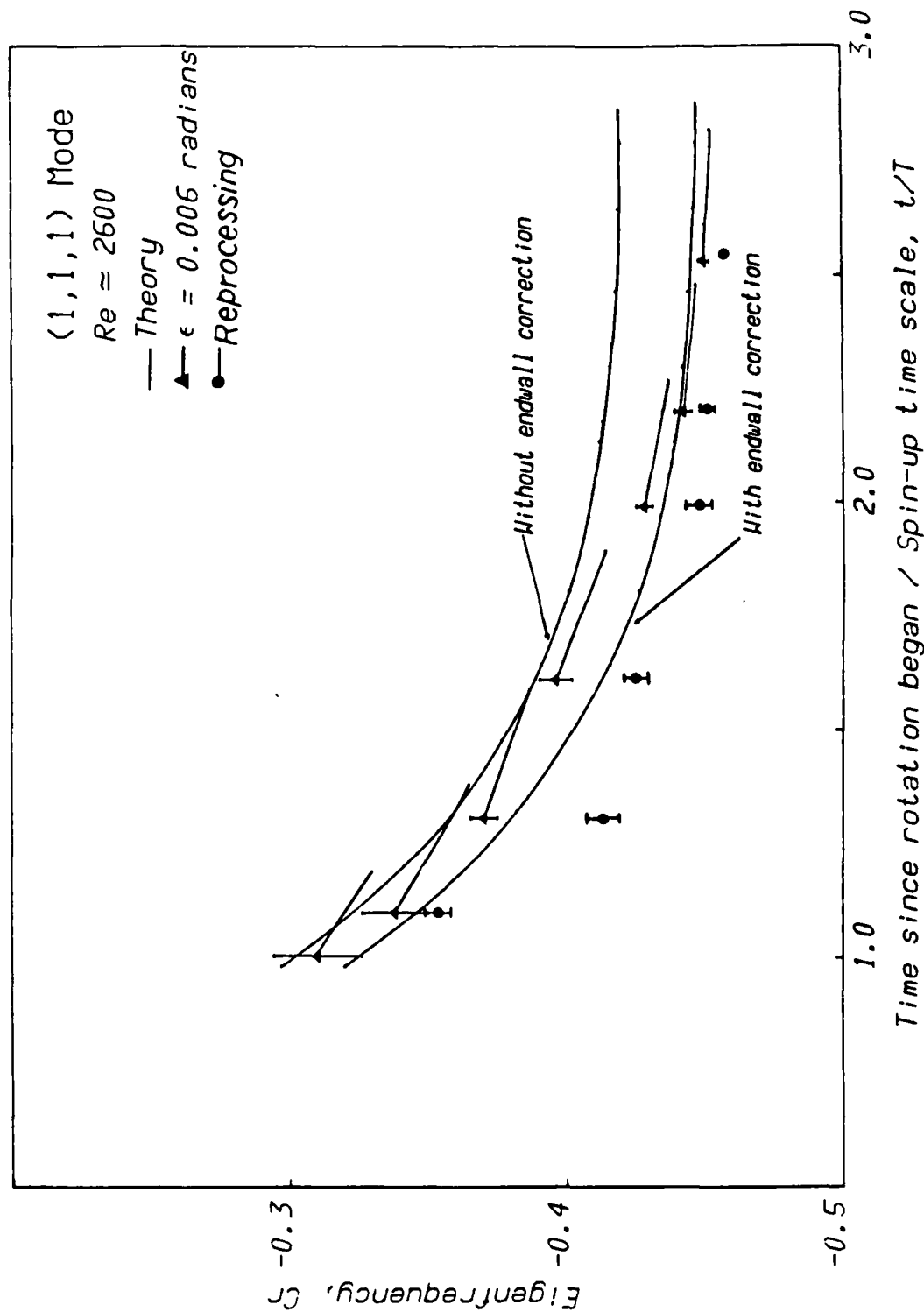Eigenfrequency dependence on time during spin-up from rest

Figure 6. Eigenfrequencies from observations by stacked record, linearized least squares (triangles), pre-filter fitting (circles) and calculation (lines) by Sedney (1983) of the (1,1,1) mode for the cylinder during spin-up from rest at Reynolds number 2600 and precession amplitude 0.006 radians.
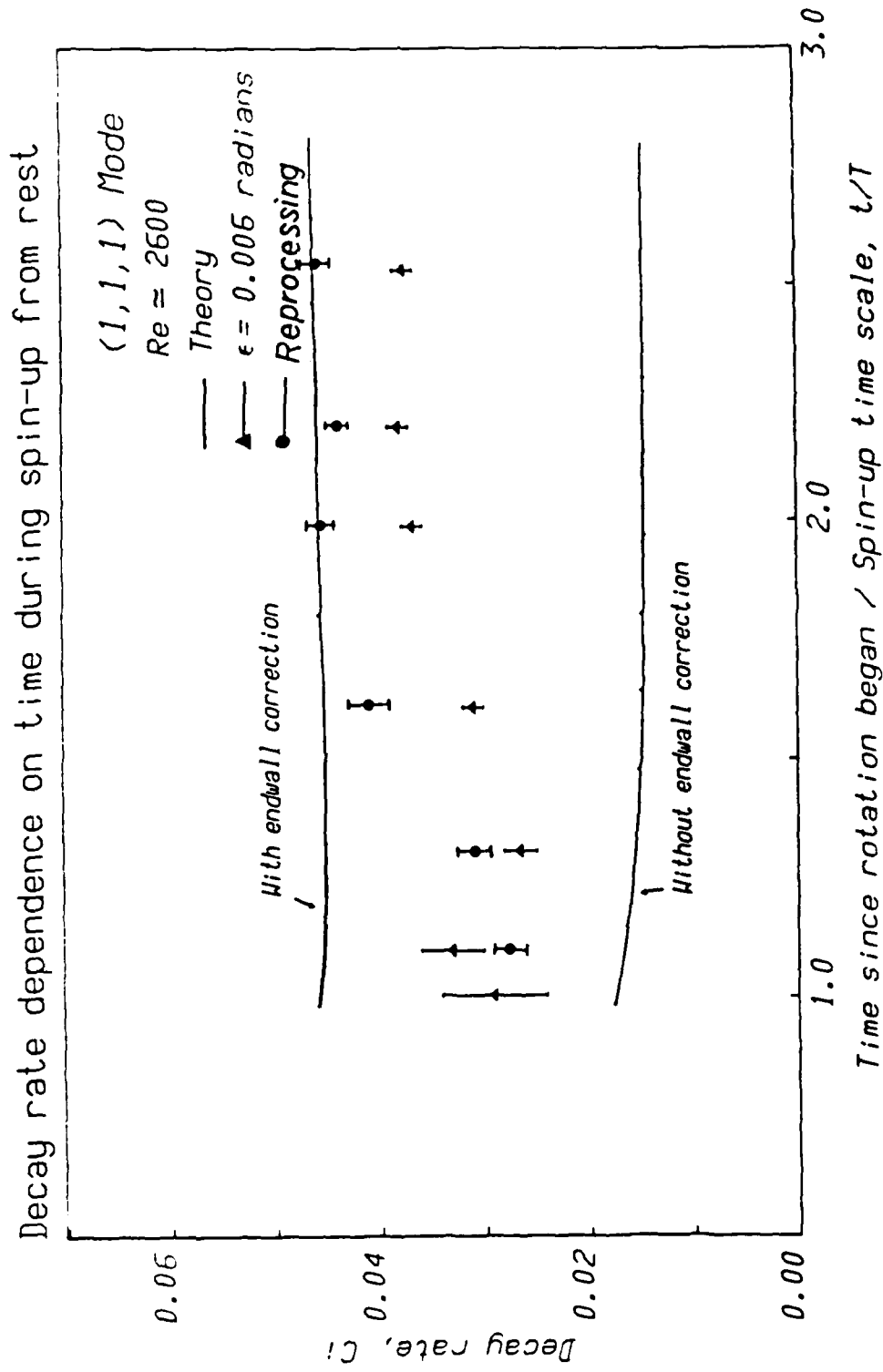
Figure 7. Decay rates from observations by stacked record, linearized least squares (triangles), prefilter fitting (circles) and calculation (lines) by Sedney (1983) of the (1,1,1) mode for the cylinder during spin-up from rest at Reynolds number 2600 and precession amplitude 0.006 radians.

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Re	t/T	$\Omega * t$	C_r	C_i
			($\pm$)	($\pm$)
2571	1.1003	67.0	-0.3534	0.0276
			(0.0049)	(0.0015)
2571	1.3090	79.7	-0.4135	0.0310
			(0.0057)	(0.0017)
2571	1.6130	98.2	-0.4249	0.0409
			(0.0046)	(0.0019)
2571	1.9926	121.3	-0.4480	0.0452
			(0.0052)	(0.0013)
2571	2.2033	134.1	-0.4515	0.0437
			(0.0037)	(0.0010)
2571	2.5410	154.6	-0.4586	0.0458
			(0.0003)	0.0015)
2433	5.9442	351.9	-0.4552	0.04527
			(0.0006)	(0.0005)
mode: (1,1,1) $\epsilon = 0.006$ radians $\Omega = 4.11$ rad/sec.				

Table 1: Pre–filter fitting results from Fig. 6 and Fig. 7

Non–Newtonian Fluid   The dependence of complex eigenfrequency on time during spin–up from rest was measured for a solution of 0.5% Sodium Carboxymethyl cellulose (CMC) in distilled water. This fluid exhibits shear thickening; the effective viscosity increases with shear stress. This is illustrated in Figure 8 obtained from measurement on the fluid using a Brookfield R.V.T. viscometer. The numbers next to each of the plotted points are values of kinematic viscosity at the measured shear rate. By contrast, Newtonian fluids, such as the silicone oils used in the rest of our experiments, would show a linear dependence of shear stress upon shear rate.

Measured eigenfrequencies for the (1,1,1) mode during spin–up from rest of the 0.5% CMC solution are plotted in Figure 9. The time since rotation of the container began is scaled with the rotation speed since the spin–up time, T, used for Newtonian fluids, is inapplicable to a non–Newtonian fluid. The eigenfrequencies shown in this figure were found from a model which represents the frequency to be constant in time for the period over which the recovery was made. Results from repeated measurements are averaged and the error bars shown reflect this process.

Figure 9 shows a decrease in eigenfrequency with time since the rotation of the container began as was the case for the (1,1,1) mode using the silicone oils. This decrease, however, takes place over a much shorter time interval than for a silicone oil. It appears that the non–Newtonian fluid shows a more step like behavior on time since the container started rotating than does a Newtonian fluid.
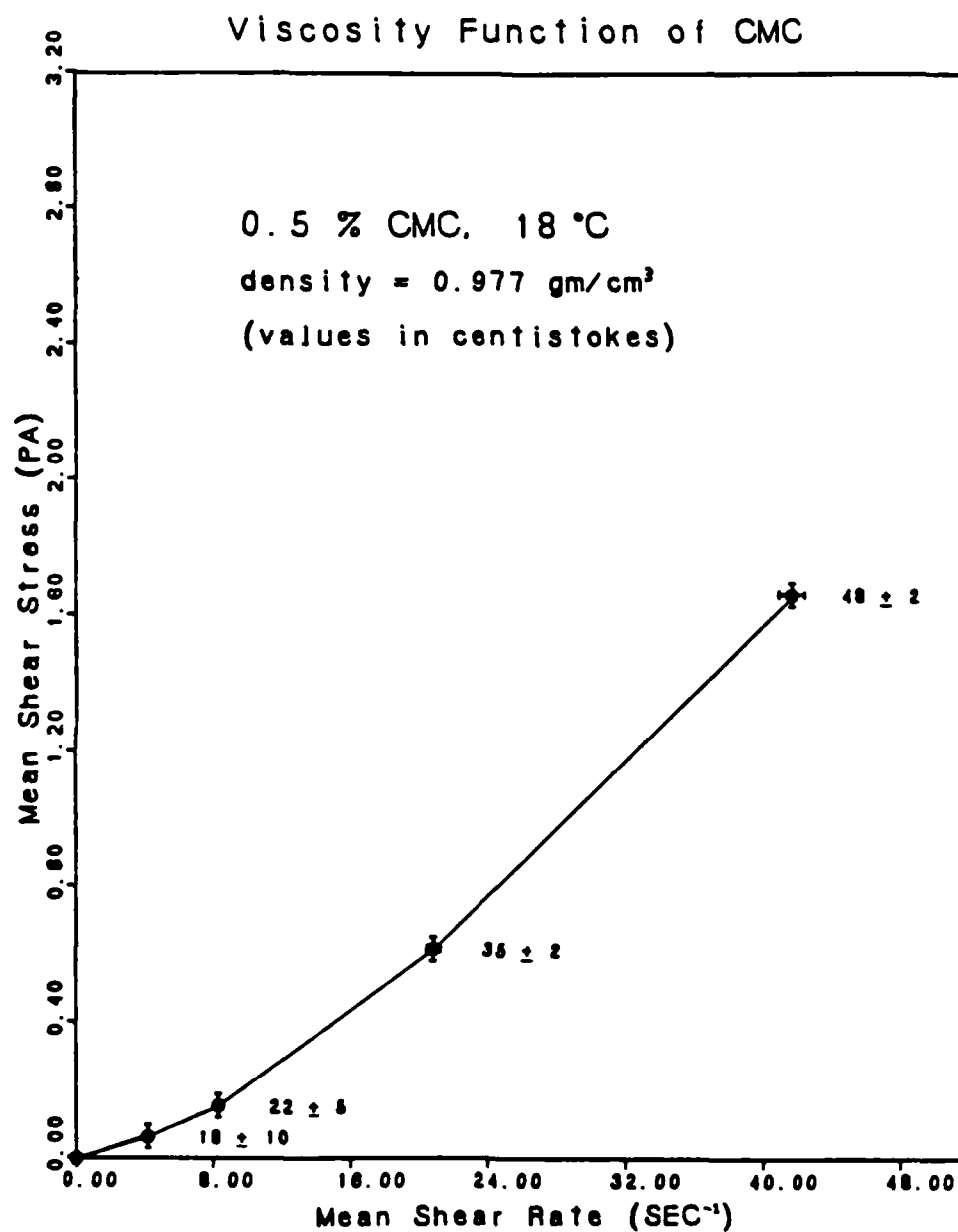
Figure 8. Relationship between mean shear stress and shear rate derived from measurements made on 0.5% Sodium Carboxymethyl cellulose solution using a Brookfield viscometer. Shear thickening of this non-newtonian fluid is shown by the convex downward shape of the curve.
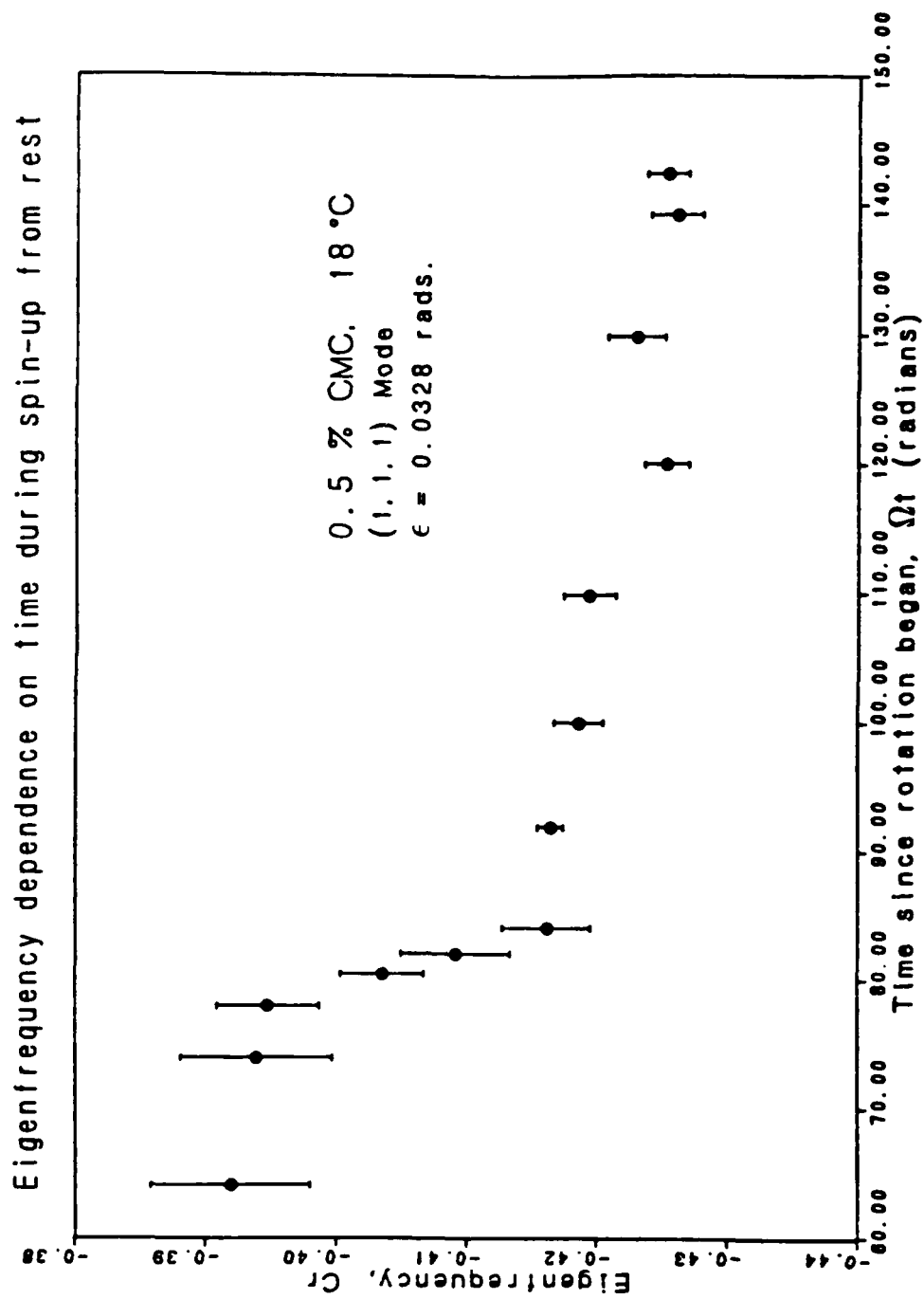
Figure 9. Measured eigenfrequencies of a non-newtonian fluid (0.5% CMC in distilled water) for the (1,1,1) mode of the cylinder during spin-up from rest. Time is measured in radians of angular position since rotation began.

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Values of C_r at the longest times shown are slightly larger than the inviscid value ($C_r = -0.4315$) for this geometry. Thus there is qualitative agreement with results for a Newtonian fluid, but our results suggest that the fluid behaves more like a Newtonian fluid of much lower viscosity than the range of values given in Figure 8.

Shown in Figure 10 is the dependence of decay rate on time since the container began rotating. The model used here for the disturbance pressure incorporates time dependence of the frequency for the mode studied. This dependence of decay rate on time is similar to that of the silicone oils but the region of rapid change of decay rate with time (around 80 radians) occurs more rapidly than for a Newtonian fluid. (The total time shown on the abscissae of Fig. 10 and Fig. 7 are about the same).

2.1.3   Resonant collapse

Resonant collapse is defined here to mean the onset of an irregular envelope of the otherwise sinusoidal disturbance pressure signal observed while the cylinder's lid was being precessed. This phenomenon was observed when the amplitude of the lid's precession was sufficiently large both while the fluid was spinning up from rest and in the steady state.

One of the most important aspects of resonant collapse is that under certain circumstances the sinusoidal disturbance can reappear in its original form after the initial onset of the collapse.
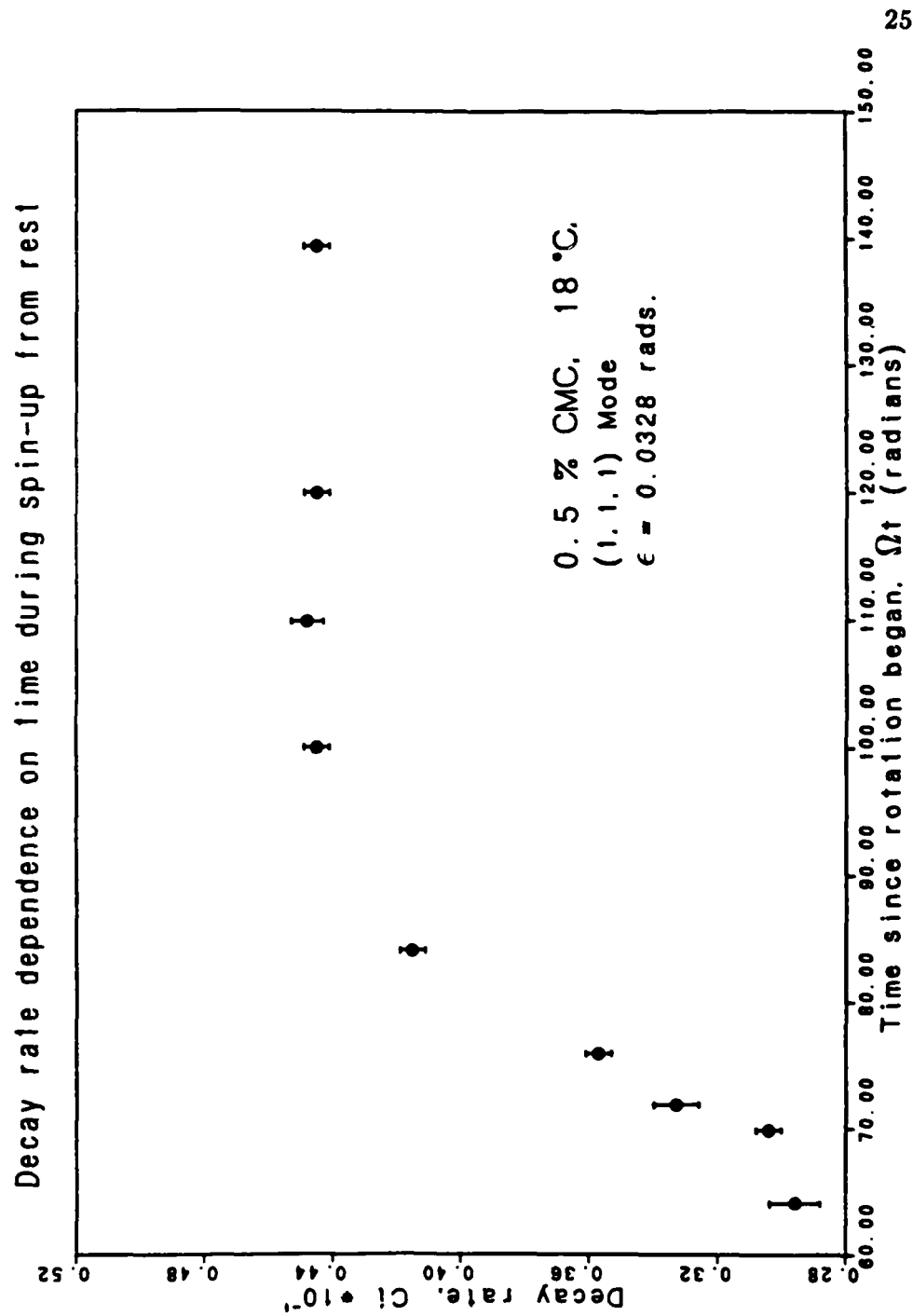
Figure 10. Measured decay rates of a non-newtonian fluid (0.5% CMC in distilled water) for the (1,1,1) mode of the cylinder during spin-up from rest. Time is measured in radians of angular position since rotation began.

This observation appears to rule out interpreting the collapse itself as an instability since there would be no v ay to account for the "recovery" of the oscillation with this mechanism.

An alternative explanation of resonant collapse is that the observed irregularity in the envelope of disturbance pressure amplitude is due to a change in the rotation rate of the fluid associated with a mean azimuthal velocity field. Observed amplitude changes are a result of change in proximity to resonance as would occur if the rotation speed were varied about a resonant value while the lid precessed at a constant frequency.

Interpretation of resonant collapse using this model required two steps of analysis. First, the mean flow associated with the inertial wave resonance had to be calculated. Second, the effect of a mean flow on the resonant frequency had to be calculated using perturbation methods. The solution of this problem is described by Gunn and Aldridge (1986).

2.2   Single Ended Pressure Measurements

Pressure measurements were made at a single point on the base of the cylinder at the same radial position as used for all the differential measurements. One port of the differential pressure transducer was left at atmospheric pressure while the other port remained connected to the fluid. The experiments using silicone oil to measure the time dependence of complex eigenfrequencies were repeated for the (1,1,1) mode. For reasons that are not fully understood at present, the resonance found in the differential measurements reported above appeared to be more difficult to find using the single ended measurements. More importantly, however, measurement of the pressure amplitude once the mode was excited during spin–up revealed a dependence of this amplitude on azimuth.

Figure 11 shows the dependence of the observed single ended pressure amplitude on azimuthal angle as measured from the highest point of the precessing lid which was stopped when the waves were allowed to decay. Linear theory from Greenspan (1969) would predict this amplitude to be a constant function of azimuth since all the inertial waves are travelling waves. The observations of Figure 11 are consistent with standing rather than travelling waves. Since the prediction of travelling waves is for a

right circular cylinder and our cylinder has a small tilt (0.0328 radians), it appears to be possible that the inertial waves might be standing for a slightly perturbed circular cylinder. Further work on single ended pressure measurements is required to resolve this point.

2.3 Possible Critical Layer

A large amplitude disturbance pressure pulse was noted just after the rotation of the container had begun and before the observation of the (1,2,1) mode. The time of occurence of this pulse was not inconsistent with that predicted by Sedney and Gerber (1985) for the critical layer associated with this mode.
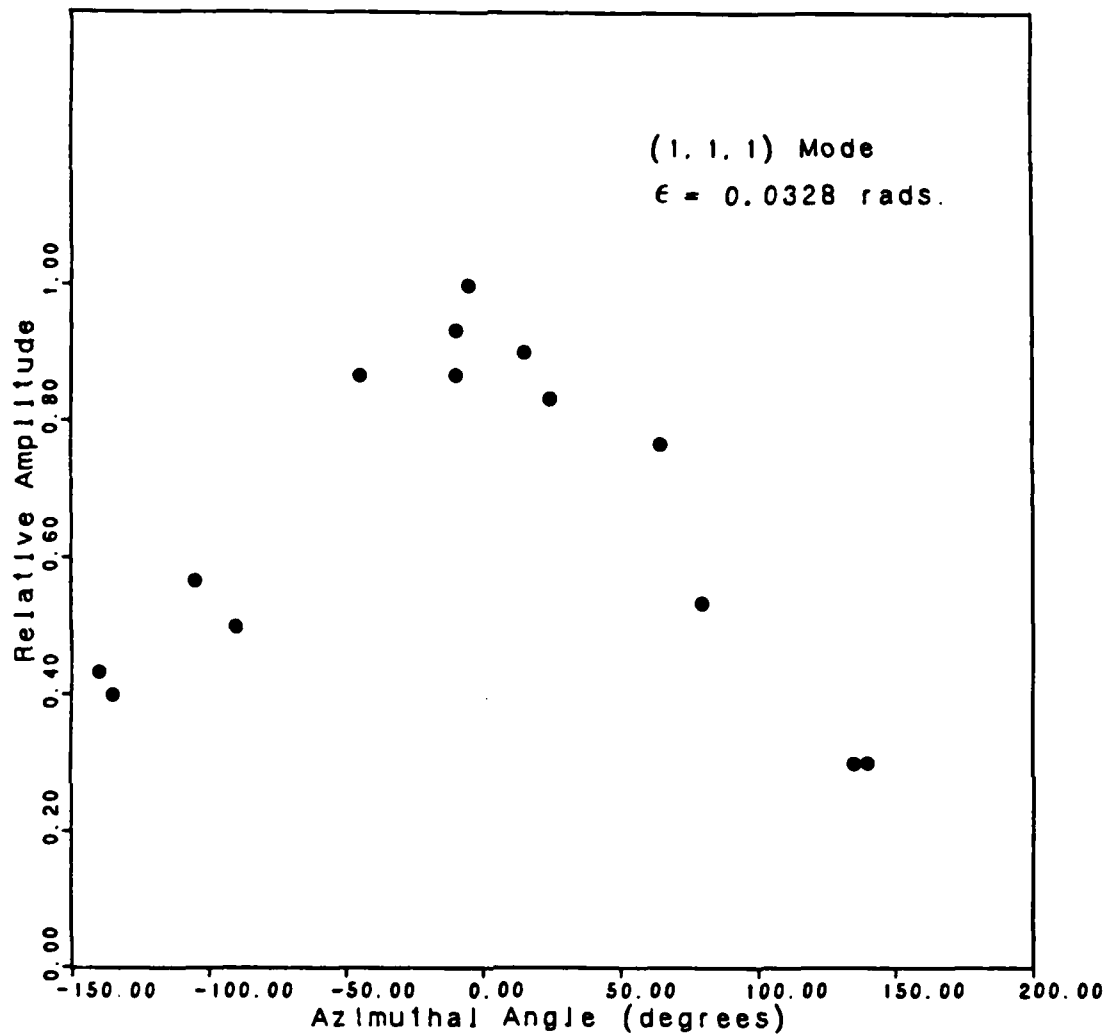
Figure 11. Evidence for standing inertial waves of a fluid contained in rotating cylindrical cavity. Points are observed pressure amplitudes at various angular positions relative to the highest elevation of the lid during free ringdown on the (1,1,1) mode.

2.4   Critical Damping

A pilot study on the critical damping of inertial waves was begun during
the course of this contract. Trapping of these waves by grooved boundaries
was tested with a small prototype model and found to significantly damp
such waves. Since the depth required to influence the waves depends on
the Elman number (or Reynolds number) the size of these grooves for a
container rotating at 80 Hz would less than 1 millimeter for a 1 centistoke
fluid. A study of the effects of boundaries on damping inertial waves is
required to determine the effectiveness of this mechanism.

3   Publications

Ringdown of Inertial Waves During Spin–Up From Rest of a Fluid Contained in a Rotating Cylindrical Cavity, S. Stergiopoulos and K. D. Aldridge, to appear in Physics of Fluids, (1986)

Direct Measurement of Time–dependent Complex Eigenfrequencies, K. D. Aldridge and S. Stergiopoulos, submitted to Geophysical and Astrophysical Fluid Dynamics, (1985)

Low Q spin–up from rest of a Fluid in a Cylindrical Cavity K. D. Aldridge, to be submitted to the Physics of Fluids.

Resonant Breakdown of Inertial Waves, S. J. Gunn and K. D. Aldridge, in preparation for the Physics of Fluids.

4 Scientific Personnel

During the course of this contract the following people have been employed as scientific personnel:

Professor Keith D. Aldridge, B.A.Sc., Ph.D (MIT), Principal Investigator, Department of Earth and Atmospheric Science

Dr. Stergios Stergiopoulos, B.S., M. Sc., Ph.D. (York), Post–doctoral fellow (Ph.D. awarded in June 1982)

Edward V. Zator, B.Sc., Research Assistant/Programmer

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